

On the Peterlin approximation for turbulent flows of polymer solutions

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We study the impact of the Peterlin approximation on the statistics of the end-to-end separation of polymers in a turbulent flow. The FENE and FENE-P models are numerically integrated along a large number of Lagrangian trajectories resulting from a direct numerical simulation of three-dimensional homogeneous isotropic turbulence. Although the FENE-P model yields results in qualitative agreement with those of the FENE model, quantitative differences emerge. The steady-state probability of large extensions is overestimated by the FENE-P model. The alignment of polymers with the eigenvectors of the rate-of-strain tensor and with the direction of vorticity is weaker when the Peterlin approximation is used. At large Weissenberg numbers, both the correlation times of the extension and of the orientation of polymers are underestimated by the FENE-P model.

I. INTRODUCTION

The addition of elastic polymers to a Newtonian solvent introduces a history dependence in the response of the fluid to a deformation and hence modifies the rheological properties of the solvent.¹ In turbulent flows, the non-Newtonian nature of polymer solutions manifests itself through a considerable reduction of the turbulent drag compared to that of the solvent alone.^{2–6} What renders this phenomenon even more remarkable is that an appreciable drag reduction can already be observed at very small polymer concentrations (of the order of a few parts per million). Turbulent drag reduction was discovered by Toms⁷ more than sixty years ago and is nowadays routinely used to reduce energy losses in crude-oil pipelines.⁸ A full understanding of turbulent drag reduction nonetheless remains a difficult challenge, because in the turbulent flow of a polymer solution the extensional dynamics of a large number of polymers is coupled with strongly nonlinear transfers of kinetic energy.

The study of turbulent flows of polymer solutions is essentially based on two approaches: the molecular approach and the continuum one. In the molecular (or Brownian Dynamics) approach, a polymer is modeled as a sequence of N beads connected by elastic springs. The deformation of the bead-spring chain is then followed along the trajectory of its center of mass. In homogeneous and isotropic turbulence, Watanabe and Gotoh⁹ have shown that $N = 2$ beads are in fact sufficient to describe the stationary statistics of both the extension and the orientation of polymers, i.e., the deformation of a polymeric chain is dominated by its slowest oscillation mode. An analogous conclusion has been reached by Terrapon et al.¹³ in a study of polymer dynamics in a turbulent channel flow. The model consisting of only $N = 2$ beads is known as the finitely extensible nonlinear elastic (FENE) dumbbell model.¹ The molecular approach is suitable for studying the deformation of passively transported polymers^{9–21}. Two-way coupling molecular simulations are a recent achievement^{22–24} and have not yet been employed in practical applications owing to their computational cost. In the molecular approach, indeed, the feedback of polymers on the velocity field is given by the forces exerted on the fluid by a huge number of polymeric chains.^{22–24}

For the above reason, in practical applications, numerical simulations of turbulent flows of polymer solutions generally use the continuum approach. The conformation of polymers is then described by means of a space- and time-dependent tensor field, which represents the average inertia tensor of polymers at a given time and position in the fluid. Such tensor is termed the polymer conformation tensor. An evolution equation for the conformation tensor may in principle be derived from the FENE dumbbell model. Such equation, however, involves the average over thermal fluctuations of a nonlinear function of the polymer end-to-end vector; a closure approximation is therefore required. Peterlin²⁵ proposed a mean-field closure according to which the average of the elastic force over thermal fluctuations is replaced by the value of the force at the mean-squared polymer extension. The resulting model was subsequently dubbed the FENE-P model.²⁶

Within the FENE-P model, the back-reaction of polymers on the flow is described by a stress tensor field, which depends on the polymer conformation tensor. This continuum model is thus suitable for simulating turbulent flows of polymer solutions; it indeed amounts to simultaneously solving the evolution equation for the polymer conformation tensor and the Navier–Stokes equation with an additional elastic-stress term. The FENE-P model is widely employed in numerical simulations of turbulent drag reduction and has been successfully applied to channel flows,^{27–30} shear flows,^{31,32} and two- and three-dimensional homogeneous and isotropic turbulence.^{33–36} Nevertheless, although it qualitatively reproduces the main features of turbulent drag reduction, the FENE-P model generally does not yield results in quantitative agreement with experimental data (e.g. Ref. 30). It is therefore essential to assess the validity of the assumptions on which the model is based.

For laminar flows, the Peterlin approximation has been examined in detail (see Refs. 37 and 38 and references therein). In particular, the FENE-P model is a good approximation of the FENE model in steady flows, whereas appreciable differences appear in time-dependent flows. This observation suggests that in turbulent flows important differences between the two models should be expected. Several studies have subsequently investigated the validity of the Peterlin approximation in turbulent flows by comparing one-way coupling simulations of the FENE and FENE-P models.^{11–13,15,19} These studies have clearly shown potential differences among FENE and FENE-P models together with high sensitivity on the statistical ensemble and dependency on the degree of homogeneity of the underlying velocity fluctuations. We undertake a systematic analysis of the Peterlin approximation in three-dimensional homogeneous and isotropic turbulence by means of one-way coupling Lagrangian simulations of the FENE and FENE-P models. The size of our statistical ensemble (128×10^3 fluid trajectories and 2×10^3 realizations of thermal noise per trajectory) allows us to fully characterize the statistics of polymer extension and orientation. When the flow is turbulent two independent effects are at the origin of the discrepancies between the FENE and FENE-P models: one is directly related to the closure approximation for the elastic force, while the other is of a statistical nature and is a consequence of deriving the statistics of polymer deformation from that of the conformation tensor. By isolating these two effects, we compare the steady-state statistics and the temporal correlation of the extension and of the orientation of polymers in the FENE and in the FENE-P model.

The rest of the paper is organized as follows. In Sect. II we briefly review the FENE and FENE-P models. The Lagrangian simulations are described in Sect. III. The results of the simulations are presented in Sect. IV. Finally, conclusions are drawn in Sect. V.

II. FENE AND FENE-P MODELS

In the FENE model, a polymer is described as two beads connected by an elastic spring, i.e., as an elastic dumbbell.¹ If the fluid is at rest, the polymer is in a coiled configuration because of entropic forces and its equilibrium extension is determined by the intensity of thermal fluctuations. If the polymer is introduced in a moving fluid and the velocity field changes over the size of the polymer, then the polymer can stretch and deform. The dynamics of the polymer thus results from the interplay between the stretching action of the velocity gradient and the elastic force, which tends to take the polymer back to its equilibrium configuration.

The maximum extension of the dumbbell is assumed to be smaller than the Kolmogorov scale, so that the velocity field changes linearly in space at the scale of the dumbbell. The drag force on the beads is given by the Stokes law. Moreover, inertial effects and hydrodynamical interactions between the beads are disregarded. Polymer–polymer hydrodynamical interactions are also disregarded under the assumption that the polymer concentration is very low. Thus, the separation vector between the beads, $\mathbf{R}(t)$, satisfies the following stochastic ordinary differential equation (the FENE equation):^{1,39}

$$\frac{d\mathbf{R}}{dt} = \sigma(t)\mathbf{R} - \frac{f(R^2)}{2\tau_p}\mathbf{R} + \sqrt{\frac{R_0^2}{\tau_p}}\boldsymbol{\xi}(t), \quad (1)$$

where $R = |\mathbf{R}|$, $\sigma_{ij}(t) = \partial_j u_i(t)$ is the velocity gradient at the position of the center of mass of the dumbbell, $\boldsymbol{\xi}(t)$ is three-dimensional white noise, R_0 is the polymer root-mean-square equilibrium extension, and τ_p is the polymer relaxation time (τ_p is the time scale that describes the exponential relaxation of $\langle R^2(t) \rangle$ to its equilibrium value in the absence of flow). The three terms on the right-hand-side of Eq. (1) represent the stretching by the velocity gradient, the restoring elastic force, and thermal noise, respectively. The function f determines the elastic force and, in the FENE model, it has the following form:

$$f(\zeta) = \frac{1}{1 - \zeta/L^2}, \quad (2)$$

where L is the maximum extension of the polymer. The elastic force diverges as R approaches L ; hence extensions greater than L are forbidden. Note that $\mathbf{R}(t)$ is a random vector and that, when \mathbf{u} is turbulent, two independent sources of randomness influence its evolution: thermal noise and the velocity gradient itself.

The polymer conformation tensor is defined as $\mathcal{C}_{ij} \equiv \langle R_i R_j \rangle_\xi$, where $\langle \cdot \rangle_\xi$ denotes an average over thermal fluctuations. To derive the evolution equation for \mathcal{C} , we apply the Itô formula to $R_i R_j$ and use Eq. (1):

$$\frac{d}{dt}(R_i R_j) = \frac{dR_i}{dt} R_j + R_i \frac{dR_j}{dt} + \frac{R_0^2}{\tau_p} \delta_{ij} = \sigma_{ik}(t) R_k R_j + \sigma_{jk}(t) R_k R_i - \frac{1}{\tau_p} f(R^2) R_i R_j + \frac{R_0^2}{\tau_p} \delta_{ij} + \sqrt{\frac{R_0^2}{\tau_p}} [R_j \xi_i(t) + R_i \xi_j(t)]. \quad (3)$$

Whereas there is no Itô–Stratonovich ambiguity for Eq. (1), Eq. (3) should be understood in the Itô sense. We now average Eq. (3) with respect to the realizations of $\boldsymbol{\xi}(t)$ and make use of the following property of the Itô integral: $\langle R_i \xi_j(t) \rangle_\xi = 0$. We thus obtain:

$$\frac{d}{dt} \langle R_i R_j \rangle_\xi = \sigma_{ik}(t) \langle R_k R_j \rangle_\xi + \sigma_{jk}(t) \langle R_k R_i \rangle_\xi - \frac{1}{\tau_p} [f(R^2) \langle R_i R_j \rangle_\xi - R_0^2 \delta_{ij}]. \quad (4)$$

Equation (4) is not closed with respect to \mathcal{C} because of the term:

$$\mathcal{A}_{ij} \equiv \langle f(R^2) R_i R_j \rangle_\xi. \quad (5)$$

To obtain a closed equation, Peterlin²⁵ proposed the following approximation:

$$\mathcal{A}_{ij} \approx f(\langle R^2 \rangle_\xi) \langle R_i R_j \rangle_\xi = f(\text{tr } \mathcal{C}) \mathcal{C}_{ij}. \quad (6)$$

The resulting evolution equation for the polymer conformation tensor (the FENE-P equation) is:

$$\frac{d\mathcal{C}^P}{dt} = \sigma(t) \mathcal{C}^P + \mathcal{C}^P \sigma^t(t) - \frac{1}{\tau_p} [f(\text{tr } \mathcal{C}^P) \mathcal{C}^P - R_0^2 \mathcal{I}], \quad (7)$$

where \mathcal{I} is the identity matrix and \mathcal{C}^P denotes the polymer conformation tensor calculated according to the Peterlin approximation. If the flow is turbulent, both \mathcal{C} and \mathcal{C}^P have a random behavior. In the following, we shall denote:

$$\mathcal{T} \equiv f(\text{tr } \mathcal{C}) \mathcal{C} \quad \text{and} \quad \mathcal{T}^P \equiv f(\text{tr } \mathcal{C}^P) \mathcal{C}^P. \quad (8)$$

Equation (7) describes the evolution of the conformation tensor of a polymer along the Lagrangian trajectory of its center of mass. Numerical simulations of drag reduction use the Eulerian counterpart of Eq. (7), which is obtained by replacing $d\mathcal{C}^P/dt$ with $\partial_t \mathcal{C}^P + \mathbf{u} \cdot \nabla \mathcal{C}^P$ and $\sigma(t)$ with the Eulerian velocity gradient. In principle, the evolution equation for the conformation tensor should be coupled with the Navier–Stokes equations through an additional stress term proportional to $\nabla \cdot \mathcal{T}^P$.¹ Here, however, we focus on the impact of the Peterlin approximation upon the statistics of polymer deformation and consider passive polymers only (one-way coupling). In the rest of the paper, we thus study the relation between Eq. (7) and Eq. (1) when $\sigma(t)$ is given by the incompressible Navier–Stokes equations in the turbulent regime. Some considerations are useful to guide our study:

1. $\mathbf{R}(t)$ cannot be calculated from the solution of the FENE-P equation (Eq. (7)). By contrast, $\mathcal{C}(t)$ can be constructed from the solution of the FENE equation (Eq. (1)) by averaging the dyadic $R_i(t) R_j(t)$ over the realizations of the noise $\boldsymbol{\xi}(t)$. The tensor $\mathcal{C}(t)$ can then be compared with $\mathcal{C}^P(t)$;
2. because of the Peterlin approximation (Eq. (6)), the FENE and FENE-P equations yield a different evolution for the conformation tensor. This holds for both laminar and turbulent flows;
3. If the flow is turbulent, the statistics of $\mathbf{R}(t)$ differs from that of $\mathcal{C}(t)$, even if $\mathcal{C}(t)$ is calculated from Eq. (1) (and hence no closure approximation is required). Consider for example the random variables $R(t)$ and $\rho(t) \equiv \sqrt{\langle R^2(t) \rangle_\xi} = \sqrt{\text{tr } \mathcal{C}(t)}$. In general, the probability density function (PDF) of $R(t)$ is different from that of $\rho(t)$, as can be seen by noting that $\langle \langle R^\alpha \rangle_\xi \rangle_\sigma \neq \langle \langle R^2 \rangle_\xi^{\frac{\alpha}{2}} \rangle_\sigma$ ($\alpha \neq 2$), where $\langle \cdot \rangle_\sigma$ denotes an average over the statistics of the turbulent velocity gradient.

In conclusion, the FENE and FENE-P models differ for two reasons: the Peterlin approximation and the statistical effect due to the fact that the statistics of $\mathbf{R}(t)$ cannot be deduced from that of $\mathcal{C}(t)$. Hence, in the turbulent regime, the proper way to examine the Peterlin approximation is to first construct $\mathcal{C}(t)$ from the FENE equation and then compare its statistics with that of the solution of the FENE-P equation. If the statistics of $\mathbf{R}(t)$ is directly compared with that of $\mathcal{C}^P(t)$, the error due to the Peterlin approximation is combined with the statistical effect discussed at point 3 above. This fact seems to have been overlooked in previous studies.

III. LAGRANGIAN SIMULATIONS

The dynamics of polymers is studied by using a database of Lagrangian trajectories that was previously generated to examine the dynamics of both tracer and inertial particles in turbulent flows.^{40,41} The turbulent velocity field is obtained by direct numerical simulation of the three-dimensional incompressible Navier–Stokes equations:

$$\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}, \quad \nabla \cdot \mathbf{u} = 0, \quad (9)$$

where p is the pressure field and $\nu = 2 \times 10^{-3}$ is the kinematic viscosity. The forcing \mathbf{f} is such that the spectral content of the first low-wavenumber shells remains constant in time. The domain is a three-dimensional periodic box of linear size 2π . Equations (9) are solved by means of a fully dealiased pseudospectral algorithm with second-order Adams–Bashforth time stepping. The number of grid points is 512^3 , while the integration time step is $dt = 4 \times 10^{-4}$. In this simulation, the Kolmogorov time is $\tau_\eta = 4.7 \times 10^{-2}$ and the Taylor-microscale Reynolds number is $R_\lambda = 185$ (for more details on the numerical simulation, see Refs. 40 and 41). We expect our results not to depend significantly on the value of R_λ except for some residual effects induced by intermittency in the statistics of the velocity gradients.⁴²

As mentioned in Sect. II, the inertia of polymers is negligible. Furthermore, their thermal diffusivity is very small compared to the turbulent diffusivity. Hence the center of mass of a polymer moves like a tracer and its position $\mathbf{x}_c(t)$ satisfies the following equation:

$$\frac{d\mathbf{x}_c}{dt} = \mathbf{u}(\mathbf{x}_c(t), t). \quad (10)$$

Equation (10) is once again solved by using a second-order Adams–Bashforth scheme; a tri-linear interpolation algorithm is used to determine the value of the velocity field at the position of the polymer.^{40,41} After the statistically stationary state is reached for both the fluid motion and the translational dynamics of polymers, the positions of the center of mass of 128×10^3 polymers are recorded every $\Delta t = 10dt = 4 \times 10^{-3} \approx \tau_\eta/10$. The total integration time after steady-state is $T = 13.2$, which corresponds to 6 eddy turnover times approximately.

The velocity gradient $\sigma(t)$ is recorded every Δt along the trajectory of the center of mass of each polymer and is inserted into Eqs. (1) and (7) in order to determine the dynamics of the separation vector and of the conformation tensor. Equation (1) is solved by using the semi-implicit predictor–corrector method introduced by Öttinger;³⁹ the integration time step is equal to Δt for all values of the parameters. The initial condition for Eq. (1) is such that $R_i(0) = R_0/\sqrt{3}$, $i = 1, 2, 3$. Equation (7) for \mathcal{C}^P is integrated by means of the semi-implicit algorithm proposed in Ref. 13, which ensures that $\text{tr} \mathcal{C}^P \leq L^2$.

The Weissenberg number is defined as $\text{Wi} \equiv \tau_p/\tau_\eta$ and is the ratio of the time scales associated with the elastic force and with the velocity gradient. In our simulations, Wi varies between 10^{-2} and 10^2 . (An alternative definition of the Weissenberg number uses the maximum Lyapunov exponent of the flow, λ , to estimate the reciprocal of the stretching time associated with the velocity gradient. In our simulations, $\lambda \approx 0.14\tau_\eta$.⁴³ Thus, the Weissenberg number based on the Lyapunov exponent is $\text{Wi}_\lambda = \lambda\tau_p \approx 0.14\text{Wi}$). The squares of the equilibrium and maximum extensions of the polymer are $R_0^2 = 1$ and $L^2 = 3 \times 10^3$, as in Refs. 9 and 19. The number of realizations of thermal noise per Lagrangian trajectory is 2×10^3 .

Finally, the statistics of polymer deformation is collected over the Lagrangian trajectories, over the realizations of thermal noise, and over time (only for times greater than the time required for $\mathbf{R}(t)$ to reach the statistically steady state).

We note that the statistics of the separation vector \mathbf{R} in isotropic turbulence has been studied thoroughly by Watanabe and Gotoh.⁹ The results on the statistics of \mathbf{R} given below agree with those presented in Ref. 9. Here, we compare the statistics of \mathcal{C} with that of \mathcal{C}^P , in order to determine the effect of the Peterlin approximation on the dynamics of polymers.

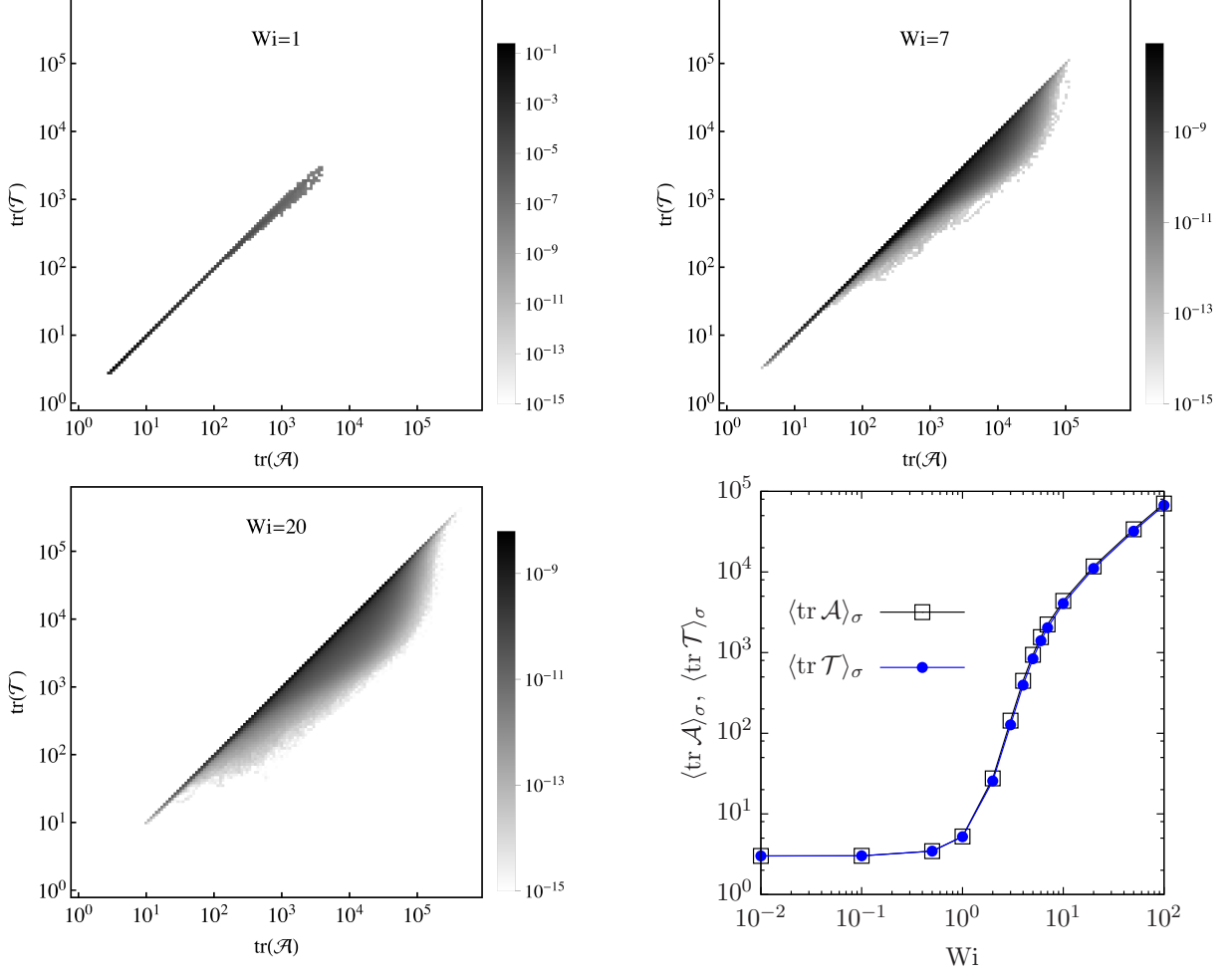


FIG. 1. Contour plot of $P_\sigma(\text{tr} \mathcal{A}, \text{tr} \mathcal{T})$ for $Wi = 1$ (top left panel), $Wi = 7$ (top right panel) and $Wi = 20$ (bottom left panel). The bottom right panel shows the averages of $\text{tr} \mathcal{A}$ (black squares) and $\text{tr} \mathcal{T}$ (blue circles) as a function of the Weissenberg number.

IV. RESULTS

In this Section, we examine the statistics of polymer extension and orientation in the FENE and FENE-P models. Before presenting the results, it is useful to define some notations. If the statistics of a random variable depends both on thermal noise and on the velocity gradient (as for instance in the case of R), its PDF is denoted as $P_{\xi, \sigma}$. If the statistics of a random variable (e.g., $\text{tr} \mathcal{C}$) only depends on the velocity gradient, then its PDF is denoted as P_σ . The auto-correlation function of a scalar random variable $X(t)$ is denoted as $F_X(t)$ and the correlation time of $X(t)$ is: $T_X = \int_0^\infty F_X(t) dt$. The auto-correlation function of a statistically isotropic, unit random vector $\mathbf{X}(t)$ is defined as:

$$F_{\mathbf{X}}(t) = 2\langle |\mathbf{X}(t + t_0) \cdot \mathbf{X}(t_0)| \rangle - 1 \quad (11)$$

and the associated correlation time is defined as: $T_{\mathbf{X}} = \int_0^\infty F_{\mathbf{X}}(t) dt$. We denote by \hat{e}_i ($i = 1, 2, 3$) the unit eigenvectors of the rate-of-strain tensor $\mathcal{S} \equiv (\nabla \mathbf{u} + \nabla \mathbf{u}^T)/2$; the unit eigenvectors \hat{e}_i are ordered by descending eigenvalue, i.e. \hat{e}_1 is associated with the largest eigenvalue of \mathcal{S} and \hat{e}_3 with the smallest one. The direction of vorticity is $\hat{\omega}$. Finally, we denote by \hat{z}_1 and \hat{z}_1^P the first unit eigenvector of \mathcal{C} and \mathcal{C}^P , respectively.

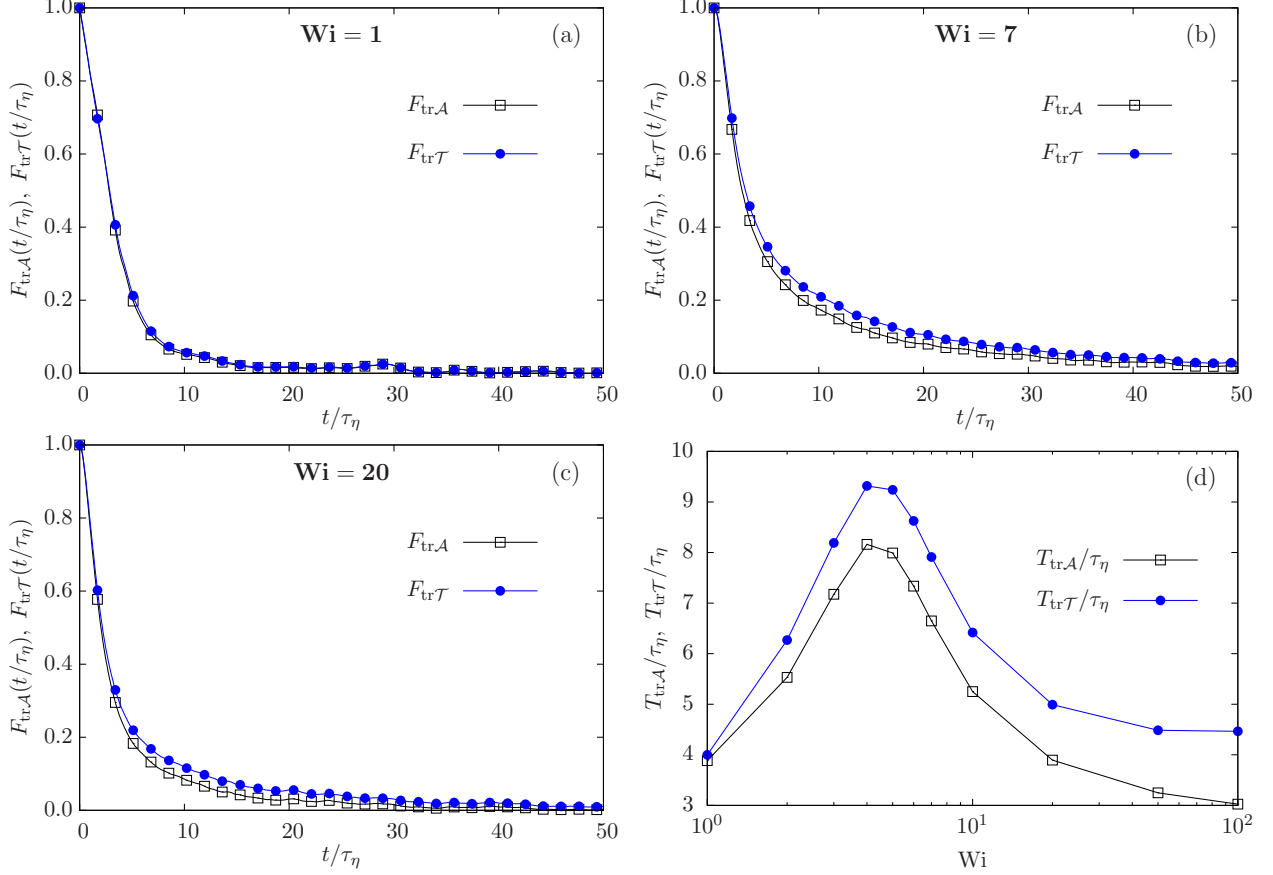


FIG. 2. Autocorrelation function of $\text{tr} \mathcal{A}$ (black squares) and $\text{tr} \mathcal{T}$ (blue circles). for (a) $Wi = 1$, (b) $Wi = 7$, (c) $Wi = 20$. Panel (d) shows the correlation times $T_{\text{tr} \mathcal{A}}$ (black squares) and $T_{\text{tr} \mathcal{T}}$ (blue circles) rescaled by τ_η as a function of Wi .

A. The Peterlin approximation

As mentioned in Sect. II, the Peterlin approximation consists in replacing \mathcal{A} with \mathcal{T} in the evolution equation for the polymer conformation tensor (\mathcal{A} and \mathcal{T} have been defined in Eqs. (6) and (8) and, up to a concentration-dependent multiplicative constant, are the polymer stress tensors in the FENE and in the FENE-P models, respectively). The eigenvectors of \mathcal{A} and \mathcal{T} are the same, but their eigenvalues may differ. Indeed, Jensen's inequality yields: $\text{tr} \mathcal{A} \geq \text{tr} \mathcal{T}$. A first indication of the effect of the Peterlin approximation is thus given by the joint PDF $P_\sigma(\text{tr} \mathcal{A}, \text{tr} \mathcal{T})$ (see Fig. 1). For small polymer extensions or for small values of Wi , $\text{tr} \mathcal{A}$ and $\text{tr} \mathcal{T}$ are approximately the same because $1 - R^2/L^2 \approx 1$; hence the Peterlin approximation holds very well. By contrast, for large extensions or for large values of Wi , the deviations of $\text{tr} \mathcal{T}$ from $\text{tr} \mathcal{A}$ are significant, i.e. the Peterlin approximation is poor. Notwithstanding, $\langle \text{tr} \mathcal{T} \rangle_\sigma$ and $\langle \text{tr} \mathcal{A} \rangle_\sigma$ do not differ appreciably (see the bottom, right panel in Fig. 1). This fact demonstrates that the study of average values may not suffice to investigate the validity of the Peterlin approximation. The full statistics of the separation vector and the conformation tensor should be investigated, which requires following the Lagrangian dynamics of a large number of polymers.

In addition, the qualitative behavior of the temporal autocorrelations of $\text{tr} \mathcal{A}$ and $\text{tr} \mathcal{T}$ are similar (Figs. 2(a) to 2(c)), but for large Wi the correlation time of $\text{tr} \mathcal{A}$ is shorter than that of $\text{tr} \mathcal{T}$ (Fig. 2(d)).

B. Statistics of polymer extension

The statistical properties of the separation R are well understood. For small values of Wi , most of polymers are in the coiled state, i.e. their extension is close to the equilibrium one. Accordingly, the PDF of

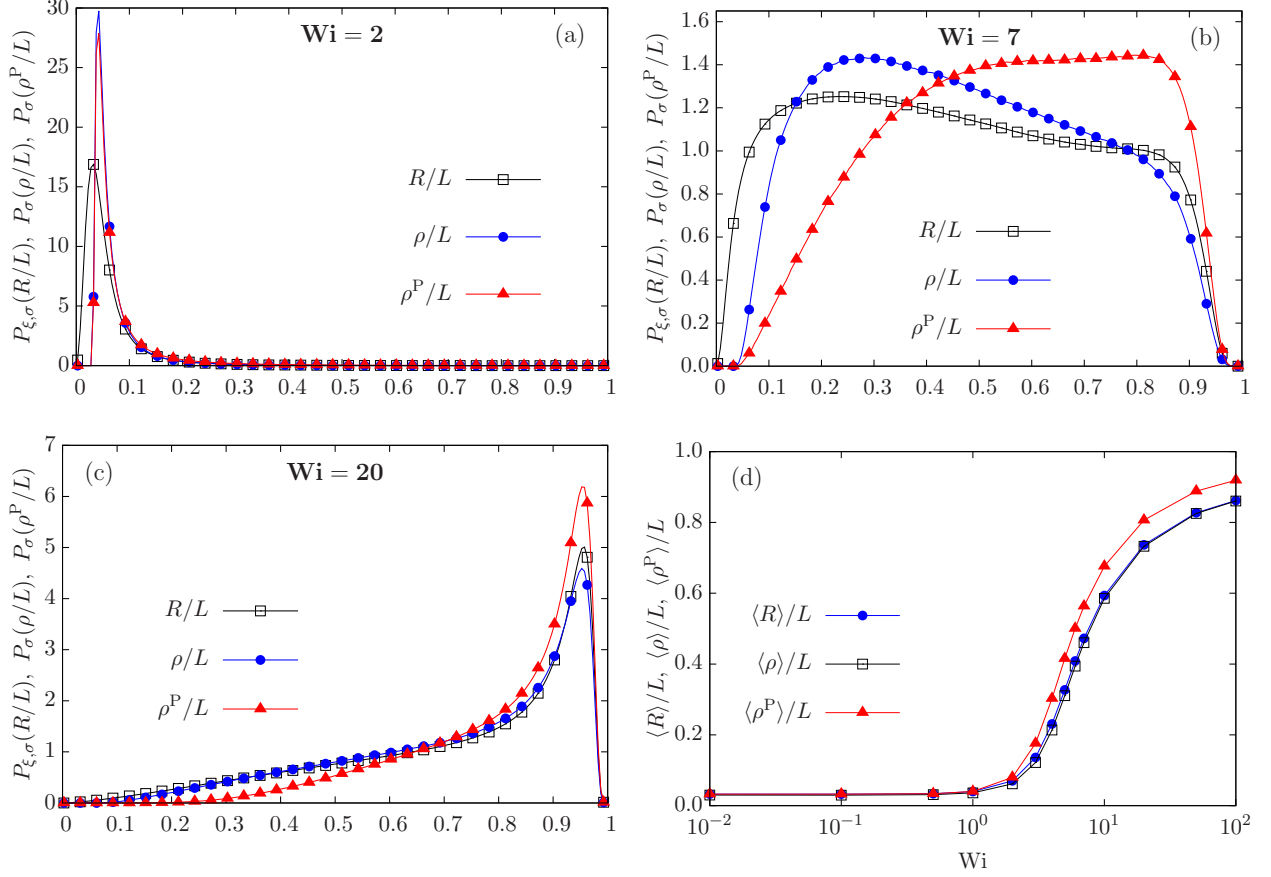


FIG. 3. PDF of R/L (black squares), ρ/L (blue circles), ρ^P/L (red triangles) for (a) $Wi = 2$, (b) $Wi = 7$, (c) $Wi = 20$. Panel (d) shows $\langle R \rangle_{\xi,\sigma}/L$ (black squares), $\langle \rho \rangle_{\sigma}/L$ (blue circles), $\langle \rho^P \rangle_{\sigma}/L$ (red triangles) as a function of the Weissenberg number.

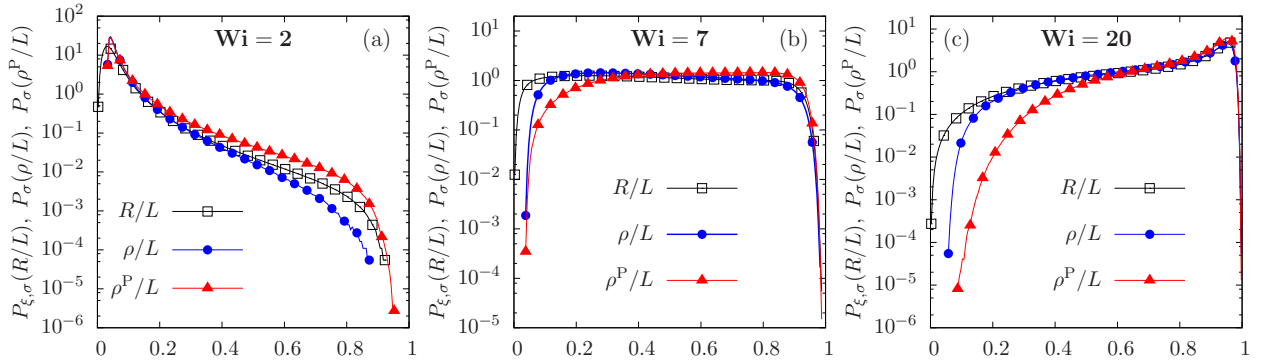


FIG. 4. PDF of R/L (black squares), ρ/L (blue circles), ρ^P/L (red triangles) in semi-logarithmic scale for (a) $Wi = 2$, (b) $Wi = 7$, (c) $Wi = 20$.

R has a pronounced peak at R_0 . As Wi increases, polymers unravel and become more and more extended. The transition from the coiled to the stretched state occurs when the Lyapunov exponent of the flow exceeds $1/2\tau_p$, i.e. at $Wi_\lambda = 1/2$.⁴⁴ (Note that some authors define the Weissenberg number in terms of the time scale associated with the exponential relaxation of $\sqrt{\langle R^2(t) \rangle}$ instead of $\langle R^2(t) \rangle$ and hence obtain a critical Weissenberg number equal to unity.)

At intermediate extensions, the PDF of R has a power-law behavior, i.e. $P_{\xi,\sigma}(R) \sim R^{-1-\alpha}$ for $R_0 \ll R \ll L$.⁴⁴ This property of $P_{\xi,\sigma}(R)$ indicates that polymers with very different extensions coexist in the fluid; whether the coiled or the stretched state dominates depends on the value of Wi . The exponent α is

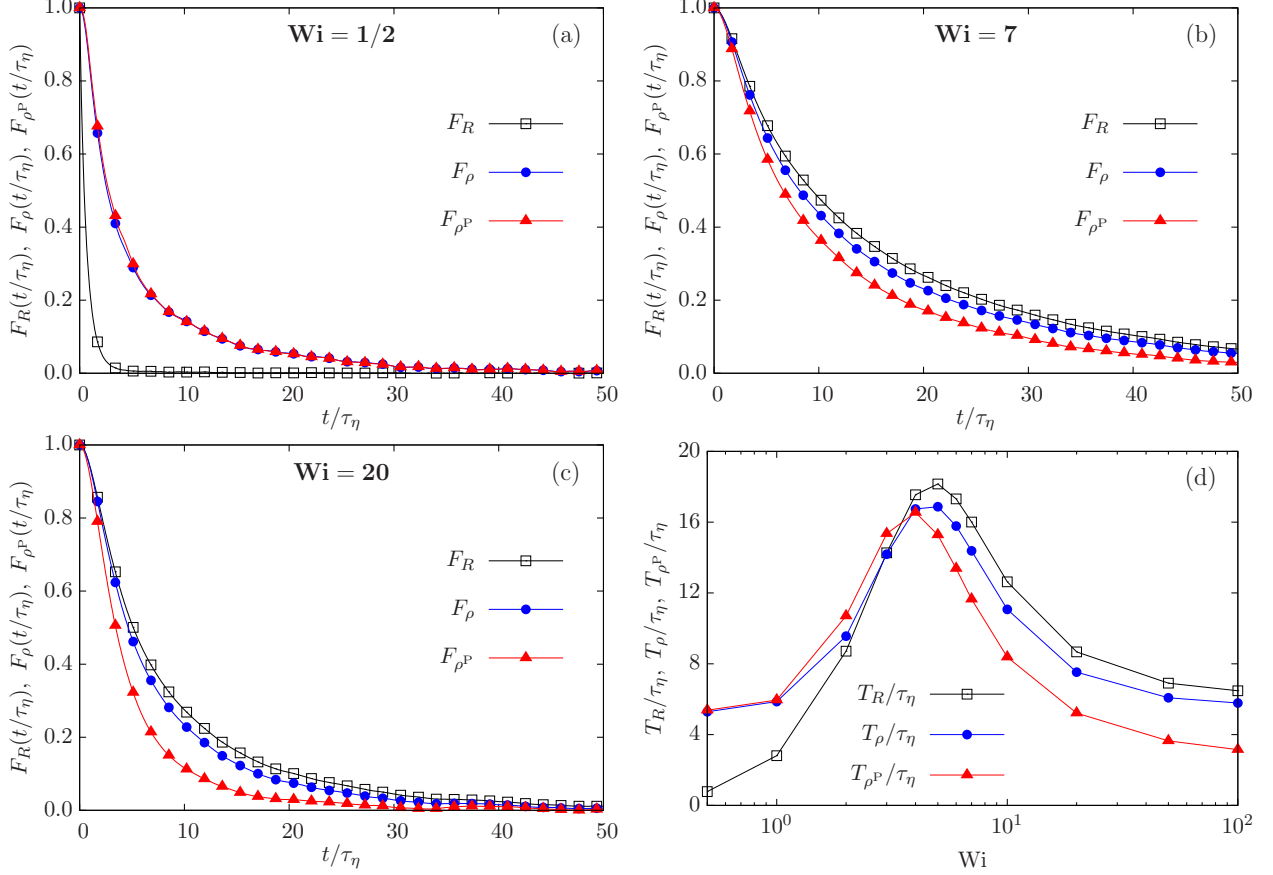


FIG. 5. Autocorrelation function of R (black squares), ρ (blue circles), ρ^P (red triangles) for (a) $Wi = 0.5$, (b) $Wi = 7$, (c) $Wi = 20$. Panel (d) shows the correlation times T_R (black squares), T_ρ (blue circles), T_{ρ^P} (red triangles) rescaled by τ_η as a function of the Weissenberg number.

positive in the coiled state and decreases as a function of Wi .^{9,20,44,45} As long as $\alpha > 0$, the FENE dumbbell model reaches a steady-state even as L tends to infinity (the $L \rightarrow \infty$ limit of the FENE model is known as the Hookean model¹). However, when α vanishes a steady-state PDF of the extension no longer exists if $L \rightarrow \infty$. This behavior is interpreted as the coil-stretch transition.⁴⁴ Finally, if Wi increases beyond the value of the coil-stretch transition, α becomes negative and the maximum of $P_{\xi,\sigma}(R)$ moves from close to R_0 to close to L .^{9,45} The statistics of R is shown in Figs. 3 and 4 for different values of Wi .

We noted in Sect. II that the comparison between the FENE and the FENE-P model ought to be done in terms of the conformation tensors \mathcal{C} and \mathcal{C}^P (rather than in terms of R and \mathcal{C}^P). Let us denote $\rho(t) = \sqrt{\text{tr} \mathcal{C}(t)}$ and $\rho^P(t) = \sqrt{\text{tr} \mathcal{C}^P(t)}$. To examine the influence of the Peterlin approximation on the statistics of polymer extension, we calculate ρ from the solution of Eq. (1) and ρ^P from Eq. (7). We then compare $P_\sigma(\rho/L)$ and $P_\sigma(\rho^P/L)$ in the steady state for different values of Wi . The plots shown in Figs. 3 and 4 correspond to the coiled state ($Wi = 2$), the coil-stretch transition ($Wi = 7$), and the stretched state ($Wi = 20$).

For small values of Wi , $P_\sigma(\rho/L)$ and $P_\sigma(\rho^P/L)$ do not differ significantly, because the extension of most of polymers is near to R_0 and hence $1 - R^2/L \approx 1$ and $\mathcal{C} \approx \mathcal{C}^P$ (Fig. 3(a)). For intermediate and large values of Wi , the statistics of R is characterized by a broad distribution of extensions around the mean value. The differences between $P_\sigma(\rho/L)$ and $P_\sigma(\rho^P/L)$, therefore, are considerable. In particular, since $\langle R^2 \rangle_{\xi,\sigma}$ is appreciably less than L^2 even for the largest Wi and $f(\zeta)$ rapidly diverges for ζ close to L [see Eq. (2)], the restoring term in Eq. (7) is weaker than that in Eq. (1). Hence, in the FENE-P model large extensions are more probable than in the FENE model to the detriment of small and intermediate extensions (Fig. 3(b) and (c)). As a consequence, the FENE-P model overestimates the average extension of polymers for large values of Wi (Fig. 3(d)). An analogous behavior of the average extension has been observed in turbulent channel flows.^{13,15}

We also note that whereas for large Wi the PDFs of R and ρ are approximately the same (Fig. 3(c)), they

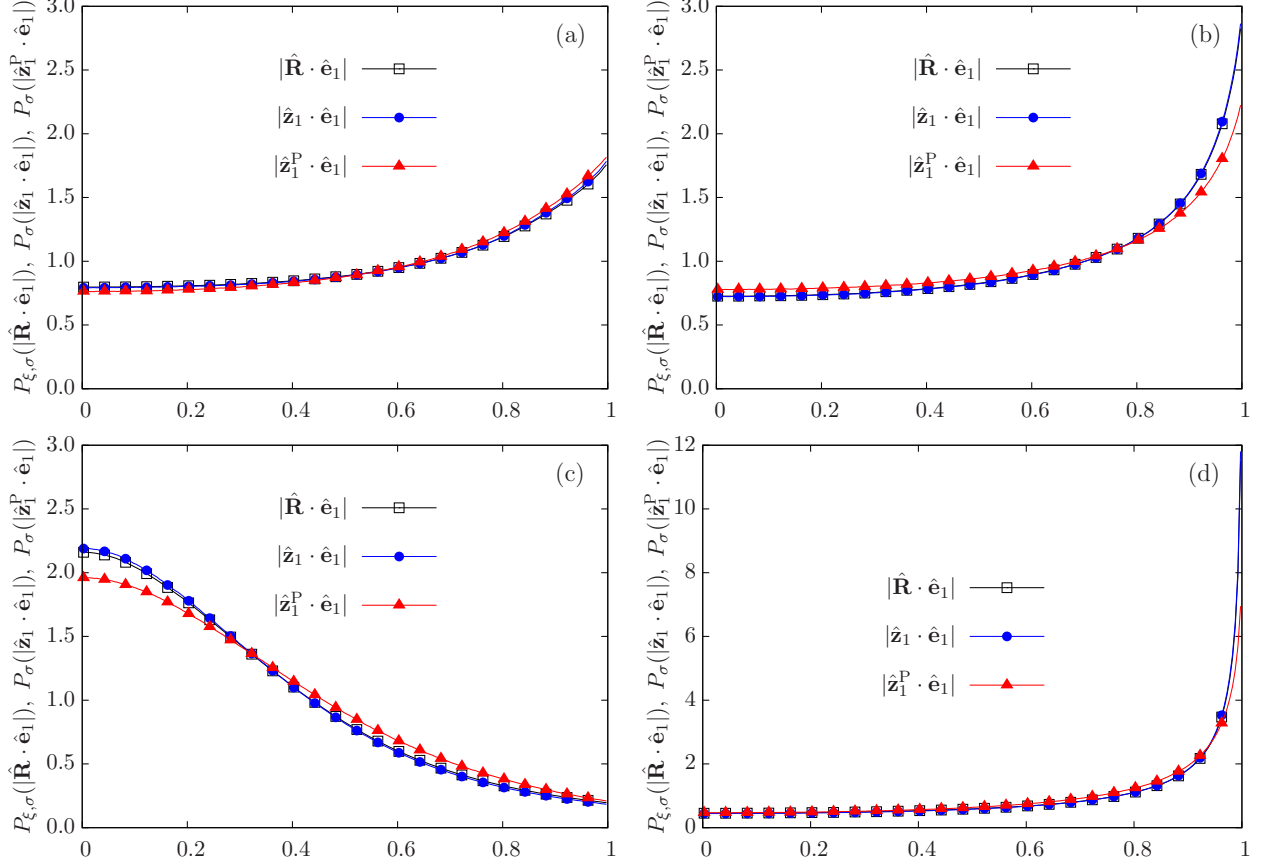


FIG. 6. PDF of alignment with (a) \hat{e}_1 , (b) \hat{e}_2 , (c) \hat{e}_3 and (d) $\hat{\omega}$ for $Wi = 20$.

are significantly different for intermediate or small Wi (Figs. 3(a) and (b)). Indeed, in the former case, the stretching action of the velocity gradient is very strong compared to the effect of thermal fluctuations, and in most realizations $R \approx \sqrt{\text{tr} \mathcal{C}}$. In the latter case, the effect of thermal fluctuations cannot be disregarded and the differences in the statistics of R and ρ (see Sect. II) become evident. Furthermore, $P_{\xi,\sigma}(R/L)$ and $P_{\sigma}(\rho/L)$ mainly differ for small and intermediate extensions, because the large extensions are obtained in those realizations in which the velocity gradient is very intense and thermal noise can be neglected. The above results demonstrate that comparing the statistics of \mathbf{R} directly with that of \mathcal{C}^P may lead to wrong conclusions; indeed, at small Wi , $P_{\xi,\sigma}(R/L)$ and $P_{\sigma}(\rho^P/L)$ are clearly different, whereas $P_{\sigma}(\rho/L)$ and $P_{\sigma}(\rho^P/L)$ are close.

The autocorrelation function of the extension is approximately exponential both in the FENE and in the FENE-P model. However, $F_{\rho^P}(t)$ is a good approximation of $F_{\rho}(t)$ only for small Wi (Fig. 5(a)). In addition, the FENE-P model captures the critical slowing down of polymers near the coil-stretch transition,^{17,46,47} but for large Wi it underestimates the correlation time of the extension (Fig. 5(d)). Once again, we note that, for small Wi , a direct comparison between $F_R(t)$ and $F_{\rho^P}(t)$ would lead to wrong conclusions about the effect of the Peterlin approximation on the temporal statistics of polymer extension.

C. Statistics of polymer orientation

In a coupled simulation of turbulent drag reduction, the feedback of polymers on the flow is of a tensorial nature; therefore, it depends not only on the extension of polymers but also on their orientation.

For small values of Wi , the separation vector \mathbf{R} exhibits a weak alignment with the eigendirections of the rate-of-strain tensor or with the vorticity,⁹ because thermal fluctuations (which are isotropic) strongly affect the dynamics. In contrast, for intermediate or large values of Wi , thermal fluctuations have a negligible effect on the dynamics of polymers. Consequently, the evolution of the extension R decouples from that of

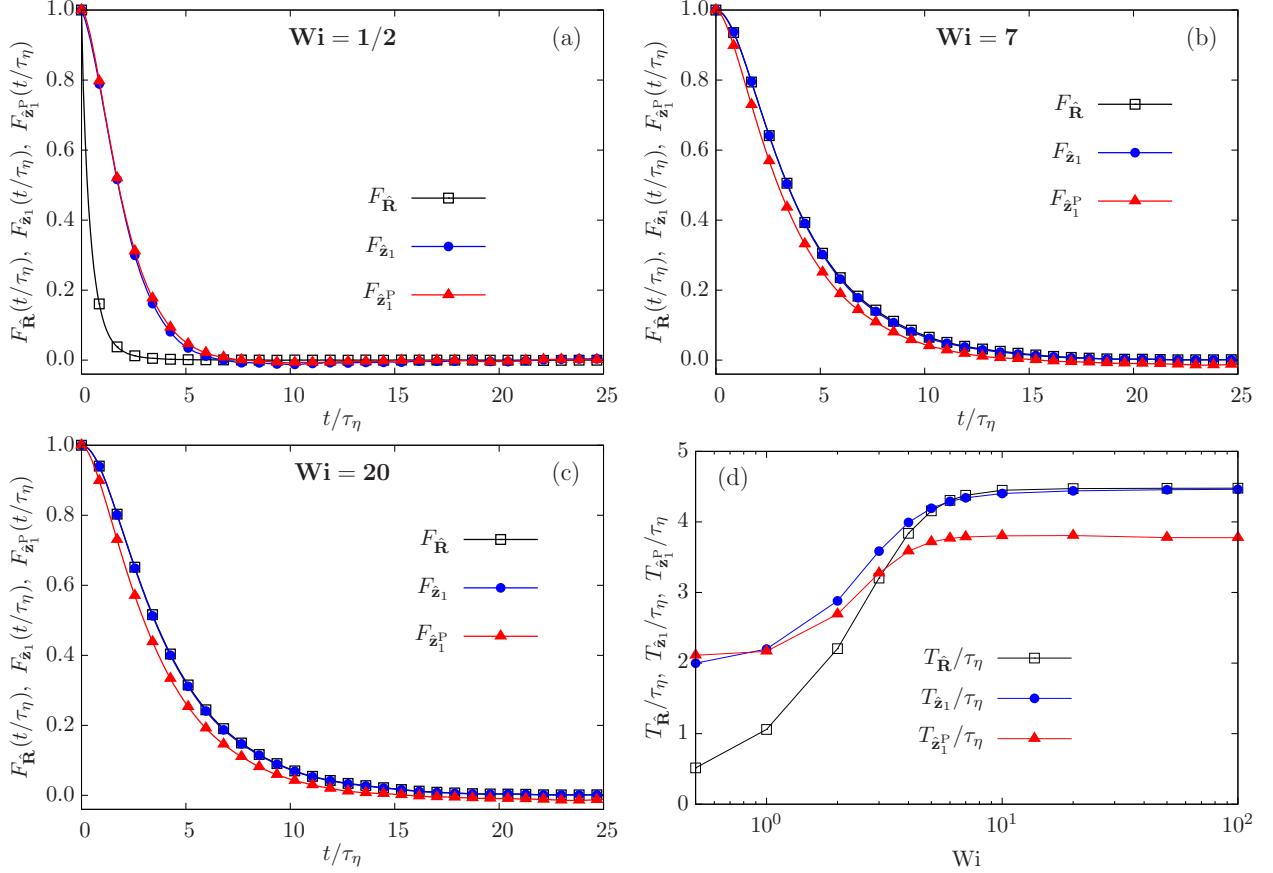


FIG. 7. Autocorrelation function of $\hat{\mathbf{R}}$ (black squares), $\hat{\mathbf{z}}_1$ (blue circles), $\hat{\mathbf{z}}_1^P$ (red triangles) for (a) $Wi = 0.5$, (b) $Wi = 7$, (c) $Wi = 20$. Panel (d) shows the correlation times $T_{\hat{\mathbf{R}}}$ (black squares), $T_{\hat{\mathbf{z}}_1}$ (blue circles), $T_{\hat{\mathbf{z}}_1^P}$ (red triangles) rescaled by τ_η as a function of the Weissenberg number.

the orientation $\hat{\mathbf{R}} = \mathbf{R}/R$, which behaves like the orientation vector of a rigid rod and is the solution of the Jeffery equation.⁴⁸ For $Wi \gtrsim 5$, the statistics of $\hat{\mathbf{R}}$ is therefore independent of Wi and coincides with that of the orientation of a rigid rod, i.e. $\hat{\mathbf{R}}$ exhibits a moderate alignment with \mathbf{e}_2 and a strong alignment with $\hat{\boldsymbol{\omega}}$ (see Refs. 9, 19, and 49 and Fig. 6).

In the FENE-P model, the first eigenvector of \mathcal{C}^P , i.e. \mathbf{z}_1^P , can be interpreted as the orientation of the polymer, provided Wi is sufficiently large. The effect of the Peterlin approximation on polymer orientation can then be studied by comparing the statistics of \mathbf{z}_1^P with that of the first eigenvector of \mathcal{C} . Fig. 6 shows that the FENE-P model qualitatively reproduces the statistics of polymer orientation but underestimates the level of alignment.

The autocorrelation function of $\hat{\mathbf{R}}$ decays exponentially (Figs. 7(a) to 7(c)), which for large Wi is in agreement with the results for the autocorrelation of the orientation of a rod.⁴⁹ The correlation time of $\hat{\mathbf{R}}$ increases for small values of Wi and saturates at large Wi (Fig. 7(d)), because for large values of the Weissenberg number the dynamics of the orientation of \mathbf{R} becomes independent of Wi . The FENE-P model agrees with the FENE model at small Wi , but quantitative discrepancies appear at large Wi (Figs. 7(a) to 7(c)). In particular, the FENE-P model underestimates the correlation time of polymer orientation (Figs. 7(d)).

V. CONCLUSIONS

Numerical simulations of turbulent flows of polymer solutions use the FENE-P model, which is based on the elastic dumbbell model but requires a closure approximation for the elastic term. We have examined the effect of the Peterlin approximation on the steady-state statistics of the extension and the orientation

of polymers. The FENE-P model captures the qualitative properties of the statistics, but for large Wi it underestimates the steady-state probability of small extensions and overestimates the probability of large extensions. As a consequence, the Peterlin approximation yields a greater average extension as well as a greater probability that polymers break under the action of a turbulent flow.⁵⁰ To quantify this effect, one would need to couple the dynamics of polymers with a fragmentation model connected to the accumulated (or instantaneous) stress along each trajectory and to estimate the relative breaking rate.⁵¹ Since large polymer extensions are more likely in the FENE-P model than in the FENE model, we also expect that the Peterlin approximation yields a stronger feedback of polymers on the flow in two-way coupling simulations of homogeneous isotropic turbulence with polymer additives. A similar argument, however, does not carry over to inhomogeneous flows like channel flows. In this case, indeed, drag reduction is caused by the strong stretching of polymers in the near wall region rather than by the dynamics in the bulk of the channel, where the flow is homogeneous and isotropic and a lower degree of stretching is observed.^{2,11–14,21}

As regards the temporal statistics of the end-to-end separation vector, both the correlation times of the extension and the orientation of polymers are underestimated by the FENE-P model. The FENE-P model also underestimates the level of alignment of polymers with the eigenvectors of the rate-of-strain tensor and with the direction of vorticity.

It would be interesting to check to what extent these properties of the FENE-P model influence the dynamics of a polymer solution by comparing two-way coupling simulations of the FENE-P model in which the stress tensor is either calculated according to the Peterlin approximation or from molecular dynamics.

In this paper, we examined the Peterlin approximation, as this is the main assumption in the construction of a continuum model of polymer solutions. However, it is worth recalling that the FENE-P model is based on the dumbbell model and hence on a very simplified coarse-grained description of a polymer macromolecule. Other approximations may thus impact the performance of the FENE-P model and its comparison with experiments. For instance, even for simple laminar flows, the dumbbell model reproduces the experimental observations only if the maximum extension and the effective bead radius are used as free parameters to fit the experimental data.^{52,53}

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